Measurement of ω meson parameters in $\pi^+\pi^-\pi^0$ decay mode with CMD-2 *

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Abstract

About 11 200 $e^+e^- \to \omega \to \pi^+\pi^-\pi^0$ events selected in the center of mass energy range from 760 to 810 MeV were used for the measurement of the ω meson parameters. The following results have been obtained: $\sigma_0 = (1457 \pm 23 \pm 19)$ nb, $m_\omega = (782.71 \pm 0.07 \pm 0.04)$ MeV/c^2, $\Gamma_\omega = (8.68 \pm 0.23 \pm 0.10)$ MeV, $\Gamma_{e^+e^-} \cdot \mathrm{Br}(\omega \to \pi^+\pi^-\pi^0) = (0.528 \pm 0.012 \pm 0.007) \cdot 10^{-3}$ MeV.

1 Introduction

High precision measurements of the ω meson parameters provide valuable information for testing various theoretical models describing interactions of light quarks. This paper presents a precise determination of the mass, total width and leptonic width of the ω, based on its dominant decay mode, $\omega \to \pi^+\pi^-\pi^0$.

The data sample was collected with the CMD-2 detector in 1994-1995 while scanning the center of mass energy range $2E_{beam}$ from 760 to 810 MeV at the high luminosity collider VEPP-2M [1]. The resonant depolarization method [2] was used for the precise calibration of the beam energy at each point. The integrated luminosity of 141 nb^{-1} corresponds to $\sim 7 \times 10^4$ ω meson decays.

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2 CMD-2 detector

The CMD-2 detector has been described in detail elsewhere [3]. It is a general purpose detector consisting of a drift chamber (DC) and proportional Z-chamber (ZC), both inside a thin (0.38 X_0) superconducting solenoid with a field of 1 T.

The barrel calorimeter placed outside the solenoid consists of 892 CsI crystals of $6 \times 6 \times 15$ cm^3 size. It covers polar angles from 0.8 to 2.3 radian. The energy resolution for photons is about 8% in the energy range from 100 to 700 MeV.

The trigger signal is generated either by the charged trigger based on DC and ZC hits [4] or by the neutral trigger [5] which takes into account the number and relative position of clusters detected in the CsI calorimeter as well as the total energy deposition. These two independent triggers have been used to study the trigger efficiency.

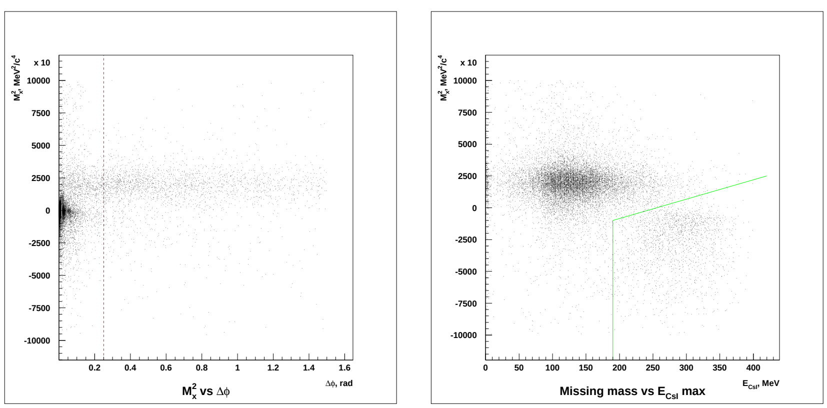
3 Analysis

Events with two tracks originating from the same vertex, each with a polar angle $0.85 < \theta < \pi - 0.85$ within the fiducial volume of the detector, were selected for further analysis.

To minimize a systematic error of the detection efficiency, only DC information has been used for the selection of $\omega \to \pi^+\pi^-\pi^0$ events. Most of the background comes from the processes with the hard photon emission:

$$e^+e^- \to e^+e^-\gamma,\ \pi^+\pi^-\gamma,\ \mu^+\mu^-\gamma.$$

These processes have the same signature as the reaction $e^+e^- \to \pi^+\pi^-\pi^0$, except for the very different acollinearity angle ($\Delta\phi = \pi - |\varphi_1 - \varphi_2|$) distribution peaked near $\Delta\phi = 0$. Thus, the rejection of events with a small $\Delta\phi$ drastically reduces the background, at the same time decreasing the number of $\pi^+\pi^-\pi^0$ events. The value of $\Delta\phi = 0.25$ was used as a reasonable compromise (see Fig. 1-a).



(a) (b)

Figure 1: Graphic presentation of cuts on $\Delta\phi$ (a) and M_X^2 vs E_{CsI}^{max} (b). (b) contains events after the cut (a). In Fig. (b) the lower right corner corresponds to rejected events.

Additional background suppression was achieved using the "$\pi^+\pi^-$ missing mass" parameter M_X which is calculated assuming charged particles to be pions and taking into account energy-momentum conservation. For real $\pi^+\pi^-\pi^0$ events the distribution of the missing mass squared has a peak in the region of $M_{\pi^0}^2$ in contrast to the background processes which have a peak around zero for $e^+e^- \to \pi^+\pi^-(\gamma)$, $\mu^+\mu^-(\gamma)$ or in the negative region for $e^+e^- \to e^+e^-(\gamma)$. Further rejection of events of the process $e^+e^- \to e^+e^-\gamma$ which has the largest cross section among the backround processes, is based on the maximum energy deposition of two charged particles in the calorimeter

E_{CsI}^{max}. The corresponding cuts shown by two lines in Fig. 1-b reject its lower right corner mostly populated by events of this background source.

The number of $\pi^+\pi^-\pi^0$ events was obtained in two different ways. The first method was to fit the M_X distributions with the sum of Gaussian functions describing $\pi^+\pi^-\pi^0$ and background events. In the second method the cosmic and beam background was rejected by fitting the distribution of the z-coordinate of the vertex with the sum of a Gaussian function and a constant background. In the last case the remaining $e^+e^- \to e^+e^-(\gamma)$, $\pi^+\pi^-(\gamma)$, $\mu^+\mu^-(\gamma)$ events were simulated and subtracted from the total number of events at each point according to the corresponding integrated luminosity. Both approaches gave the same result within statistical errors.

At each energy the $\pi^+\pi^-\pi^0$ production cross section was calculated according to the formula:

$$\sigma(e^+e^- \to \pi^+\pi^-\pi^0) = \frac{N_{\pi^+\pi^-\pi^0}}{L \cdot \varepsilon_{trig} \cdot \varepsilon_{MC} \cdot \varepsilon_{M_X^2} \cdot (1+\delta_{rad})},$$

where $N_{\pi^+\pi^-\pi^0}$ is the number of events; L is the integrated luminosity determined from large angle Bhabha events with the help of the procedure described in [6]; δ_{rad} is the radiative correction calculated according to [7] with an accuracy better than 0.5%; and ε_{trig}, ε_{MC}, $\varepsilon_{M_X^2}$ are respectively the trigger efficiency, the geometrical efficiency (acceptance) multiplied by the reconstruction efficiency, and the efficiency of the cut shown in Fig. 1-b. The acceptance is the probability to detect two pions from the ω decay within a given solid angle. It was calculated by Monte Carlo simulation taking into account radiative photons emitted by initial electrons.

The efficiencies ε_{MC} and $\varepsilon_{M_X^2}$ were calculated by Monte Carlo simulation. Their systematic errors were estimated with the help of special "test" events obtained as a result of the constrained fit based on the information from the ZC and CsI calorimeter only. About 40% of the $\pi^+\pi^-\pi^0$ events have two clusters in the CsI calorimeter resulting from a neutral pion decay. Using the polar and azimuthal angles of these clusters as well as the hits of charged tracks in the ZC, one can reconstruct the $\omega \to \pi^+\pi^-\pi^0$ event without DC information. “Test” events with the neutral trigger were also used to determine the charged trigger efficiency.

Typical values of the efficiencies and corrections are presented in Table 1 for $2E_{beam}$ = 782.0 MeV (the ω meson peak).

Table 1: Efficiencies, corrections and their errors at $2E_{beam} = 782.0$ MeV

Efficiency	Value, %	Stat. error, %	Syst. error, %
ε_{MC}	19.0	0.1	0.1
ε_{trig}	99.5	0.2	0.1
$\varepsilon_{M_X^2}$	99.2	0.2	0.2
$1+\delta_{rad}$	78.5	0.1	0.5

The integrated luminosity, radiative correction, number of selected $\pi^+\pi^-\pi^0$ events and cross section for $e^+e^- \to \omega \to \pi^+\pi^-\pi^0$ at each energy are presented in Table 2.

4 ω meson parameters

The experimental data were fitted with a function which includes the interference of the ω and ϕ mesons and non-resonant background:

$$\sigma_{3\pi}(s) = \frac{F_{3\pi}(s)}{s^{3/2}} \cdot |A_\omega + e^{i\alpha}A_\phi + A_{bg}|^2, \qquad (1)$$

$$A_V = \frac{m_V^2\Gamma_V\sqrt{\sigma_V m_V/F_{3\pi}(m_V^2)}}{s - m_V^2 + i\sqrt{s}\Gamma_V(s)},$$

$$A_{bg} = m_\omega^{3/2}\sqrt{\sigma_{bg}/F_{3\pi}(m_\omega^2)},$$

Table 2: Integrated luminosity, radiative correction, number of events and cross section for $e^+e^- \to \pi^+\pi^-\pi^0$

E_{beam}, MeV	$\int Ldt$, nb^{-1}	δ_{rad}	$N_{\pi^+\pi^-\pi^0}$	$\sigma(\omega \to \pi^+\pi^-\pi^0)$, nb
380.092	6.20±0.10	-0.183	64±11	67±11
382.083	10.79±0.14	-0.191	115±13	69±8
385.053	8.23±0.12	-0.206	216±17	175±15
387.190	6.50±0.11	-0.220	263±18	272±21
389.087	6.62±0.11	-0.232	739±29	771±40
390.087	7.03±0.11	-0.232	1155±35	1165±50
391.113	19.03±0.18	-0.215	4080±65	1455±30
392.119	10.43±0.14	-0.172	2104±47	1306±44
393.018	5.17±0.09	-0.116	753±28	882±43
395.047	9.31±0.12	0.031	747±29	407±19
397.068	9.17±0.08	0.178	403±22	192±11
400.000	9.75±0.12	0.358	313±19	124±8
405.071	14.29±0.15	0.613	244±18	55±4

$$\Gamma_\omega(s) = \Gamma_\omega \cdot \left(Br_{\pi^+\pi^-} \frac{m_\omega^2 F_{2\pi}(s)}{s F_{2\pi}(m_\omega^2)} + Br_{\pi^0\gamma} \frac{F_{\pi^0\gamma}(s)}{F_{\pi^0\gamma}(m_\omega^2)} + Br_{3\pi} \frac{\sqrt{s} F_{3\pi}(s)}{m_\omega F_{3\pi}(m_\omega^2)} \right),$$

$$F_{\pi^0\gamma}(s) = (\sqrt{s}(1 - m_{\pi^0}^2/s))^3,\; F_{2\pi}(s) = (s/4 - m_\pi^2)^{3/2},$$

where m_V, Γ_V, σ_V are mass, width and peak cross section ($s = m_V^2$) for the vector meson ω or ϕ; α is a relative phase of $\omega - \phi$ mixing taken to be $(155 \pm 15)^\circ$ according to [8]. $F_{3\pi}(s)$ is a smooth function which describes the dynamics of $V \to \rho\pi \to \pi^+\pi^-\pi^0$ decay including the phase space [9]. $\Gamma_\phi(s)$ has been parametrized similarly to ω using the corresponding branching ratios and phase space factors [10].

The cross section values were fit by the function (1). The ω meson mass, width, peak cross section and background cross section were optimized, while the ϕ meson parameters were fixed at their world average values [11].

The energy dependence of the cross section is shown in Fig. 2 (experimental points and the optimal fitting curve). The following ω meson parameters were obtained from the fit:
$\sigma_0 = (1457 \pm 23)$ nb, $M_\omega = (782.71 \pm 0.07)$ MeV/c^2, $\Gamma_\omega = (8.68 \pm 0.23)$ MeV, $\sigma_{bg} = (12 \pm 5)$ nb.

The systematic error of σ_0 is about 1.3% and comes from the following sources:

reconstruction efficiency	0.5% ;
trigger efficiency	0.1% ;
radiative corrections for the process $e^+e^- \to \pi^+\pi^-\pi^0$	0.5% ;
decays in flight	0.1% ;
pion nuclear interaction	0.2% ;
solid angle uncertainty	0.3% ;
luminosity determination	1.0% .

The systematic error of the mass was found to be about 40 keV dominated by the stability of the beam energy.

The systematic error of the width was found to be about 100 keV dominated by the scatter of results of various fits corresponding to different selection criteria.

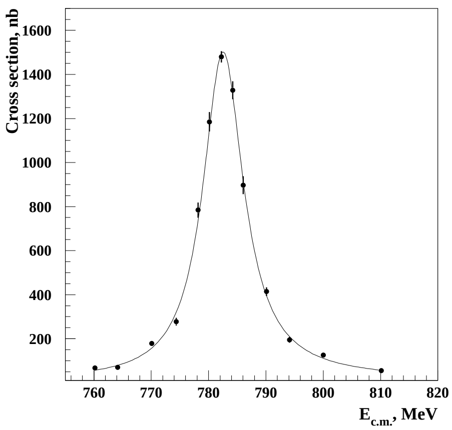


Figure 2: ω meson excitation curve

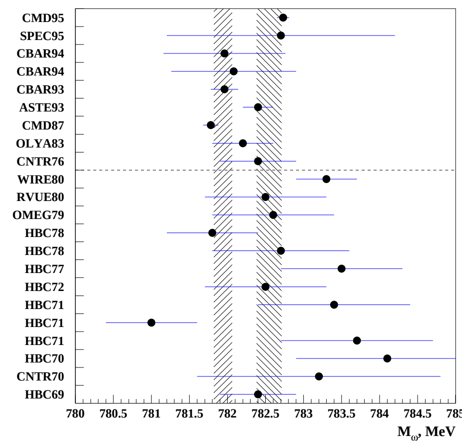


Figure 3: Experimental data on the ω meson mass. The left shaded bar corresponds to the current world average [11], the right one — to the world average before the CMD87 experiment. This work (CMD95) and experiments below the dashed line are not used for the current world average.

5 Discussion

The measurements of $\sigma_0(\omega \to \pi^+\pi^-\pi^0)$ have been performed by a number of groups from Orsay and Novosibirsk with the results presented in Table 3. One can see that the result of this work

Table 3: Results of σ_0 measurements by various groups

Group	$\sigma_0(e^+e^- \to \omega \to \pi^+\pi^-\pi^0)$, nb	Reference
OSPK1,1969	1590 ± 165	[12]
OSPK2,1972	1800 ± 200	[13]
DM1,1980	1410 ± 130	[14]
OLYA,1982	1390 ± 100	[15]
OLYA,1984	1420 ± 100	[16]
CMD, 1987	1549 ± 57	[17]
ND, 1989	1530 ± 77	[8]
CMD-2	1457 ± 30	This work

$\sigma_0(\omega \to \pi^+\pi^-\pi^0) = (1457 \pm 30)$ nb does not contradict these measurements and is the most precise.

The cross section in the peak obtained in our experiment is related to the product $\Gamma_{e^+e^-} \cdot \mathrm{Br}(\omega \to \pi^+\pi^-\pi^0)$. To obtain this value, the fit with this product as a free parameter has been performed with the following result:

$$\Gamma_{e^+e^-} \cdot \mathrm{Br}(\omega \to \pi^+\pi^-\pi^0) = (0.528 \pm 0.012 \pm 0.007)\,\mathrm{keV}\,,$$

which is the most precise direct measurement of this quantity. Using $\Gamma_{e^+e^-}$ from other experiments, one can obtain $Br(\omega \to \pi^+\pi^-\pi^0)$. For example, for $\Gamma_{e^+e^-} = (0.60 \pm 0.02)$ keV from [11], $Br(\omega \to$

$\pi^+\pi^-\pi^0) = 0.880 \pm 0.020 \pm 0.032$ can be obtained. Alternatively, taking $Br(\omega \to \pi^+\pi^-\pi^0)$ from other measurements, $\Gamma_{e^+e^-}$ can be calculated. For $Br(\omega \to \pi^+\pi^-\pi^0) = 0.888 \pm 0.007$ (from [11]), we obtain for the leptonic width $\Gamma_{e^+e^-} = (0.595 \pm 0.014 \pm 0.009)$ keV or for the leptonic branching ratio $\Gamma_{e^+e^-}/\Gamma_\omega = (6.85 \pm 0.11 \pm 0.11) \cdot 10^{-5}$.

In Fig. 3 the result of this work (CMD95) is compared to the previous measurements of the ω meson mass. The left shaded bar corresponds to the current world average. Its value is dominated by the CMD87 experiment which was also performed at the VEPP-2M collider with the CMD detector [17]. The reported precision of CMD87 was much better than in all other experiments. Our new measurement gives the ω meson mass value 930 keV higher (more than seven standard deviations) than in CMD87.

Since both measurements were performed at VEPP-2M and used the resonant depolarization method (RDM), thorough comparison of two experiments has been carried out.

We now assume that the difference between the two results is due to the fact that resonant depolarization method (RDM) measurements in CMD87 were regularly performed at some side band resonance. Such a resonance could arise from a parasitic modulation of the depolarizer frequency since the RF device used for the RDM had the power about $10^4 - 10^5$ times higher than required. Thus, the absolute calibration of the beam energy gave wrong results.

Unfortunately, after a lapse of more than ten years, it is impossible to reproduce the CMD87 environment and prove the above hypothesis. However, we know that because of various technical problems inadequate attention was given at that time to the possibility of the low modulation leading to a side band resonance.

Since the time of the CMD87 experiment, the VEPP-2M collider and the RDM hardware have been upgraded. The applied RF power is of the order of a few mW excluding any "parasitic" depolarization. Furthermore, the frequency spectrum of the depolarizer was investigated before the RDM measurements and we believe that in the present experiment the sources of the systematic error in RDM considered above have been completely removed.

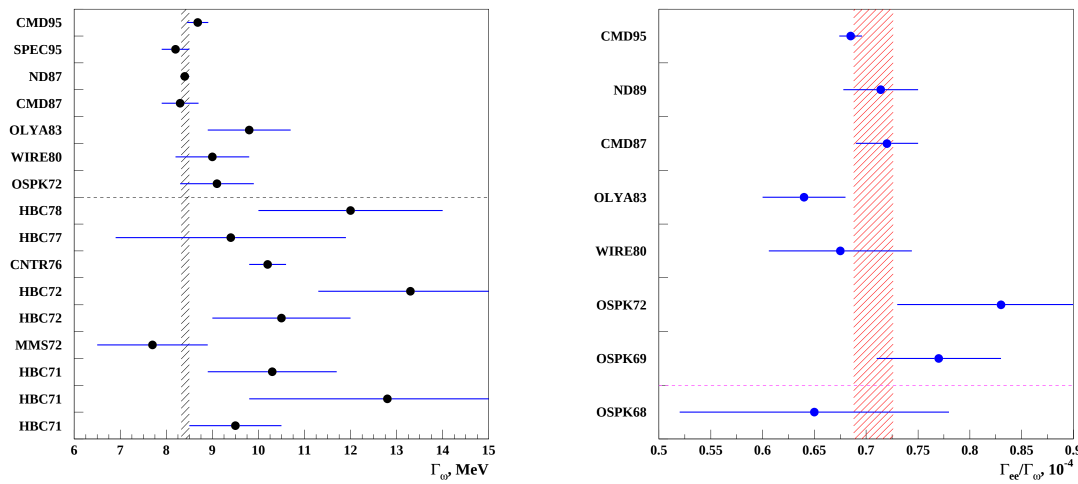
There were also some other differences between the RDM measurements in both experiments. In CMD87 the beam was polarized in the VEPP-2M ring itself at the beam energy of about 700 MeV. This led to variations of the collider parameters before each RDM measurement including the change of the betatron frequencies ν_x, ν_z in order to pass through intrinsic spin resonances. The imperfection resonance at the "magic energy" $E_{beam} = 440.65$ MeV was crossed adiabatically by decompensating the longitudinal magnetic field of the detector (so called "partial siberian snake" mode [18]). Another parameter affecting the beam energy was the collider temperature which changed by approximately 10° C between the polarization at the high energy and a subsequent RDM measurement.

In the present experiment the beam was polarized in the new booster ring at the high energy and after that injected into VEPP-2M at the energy of the experiment. Thus, the parameters of the collider itself were not changed and RDM measurements were performed under the same conditions as data taking.

The beam energy stability during data taking has been thoroughly analysed. This analysis was based both on the deviations of about 60 RDM measurements at different energies from the predicted values and on direct measurements of the beam energy stability by the tracking system of the CMD-2 detector [6]. The RDM measurements were consistent with each other in the energy range covering the ω and ϕ mesons and showed the long-term beam energy instability of the order of 50 keV. The latter was used as an uncertainty of the beam energy at each point for the calculation of the ω meson mass systematic error.

The value of the ω meson mass obtained in this work is close to the world average before the CMD87 experiment $M_\omega = (782.55 \pm 0.17)$ MeV$/c^2$ (the right shaded bar in Fig. 3) and is the most precise today.

The results of this work on the total width of the ω meson (Fig. 4-a) as well as on the leptonic branching ratio $\Gamma_{e^+e^-}/\Gamma_\omega$ (Fig. 4-b) are in good agreement with those from previous experiments.



(a) ω-meson total width

(b) Leptonic branching ratio $\Gamma_{e^+e^-}/\Gamma_\omega$

Figure 4: Experimental data on the ω meson total width (a) and leptonic branching ratio (b). Vertical shaded bars correspond to the current world averages [11]. The results of this work (CMD95) and of experiments below the dashed line are not used for averages.

6 Conclusion

Using the CMD-2 data sample of about 11 200 $\omega \to \pi^+\pi^-\pi^0$ events, the following values of the ω meson parameters have been obtained:

$$
\begin{aligned}
\sigma_0 &= (1457 \pm 23 \pm 19)\,\text{nb}, \\
M_\omega &= (782.71 \pm 0.07 \pm 0.04)\,\text{MeV}/c^2, \\
\Gamma_\omega &= (8.68 \pm 0.23 \pm 0.10)\,\text{MeV}, \\
\Gamma_{e^+e^-} \cdot Br(\omega \to \pi^+\pi^-\pi^0) &= (0.528 \pm 0.012 \pm 0.007) \cdot 10^{-3}\,\text{MeV}.
\end{aligned}
$$

These results, except for the total width, are more precise than those from previous experiments. The mass value differs significantly from the previous most precise measurement [17] which was performed by a group including many authors of this work. Due to the present more thorough study of systematic errors, our mass measurement supersedes that of Ref. [17].

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